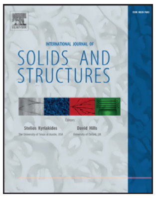
International Journal of Solids and Structures 000 (2018) 1–19

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr



Evaluating continuum level descriptions of the medial collateral ligament

Benjamin C. Marchi[a,*], Callan M. Luetkemeyer[a], Ellen M. Arruda[a,b,c]

[a] Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA
[b] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI 48109, USA
[c] Program in Macromolecular Science and Engineering, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 14 September 2017
Revised 1 December 2017
Available online xxx

Keywords:
Constitutive modeling
Ligament
Biomechanics
Orthotropic hyperelasticity

ABSTRACT

Soft tissues of the knee contain complex physiological microstructures with nontrivial hierarchical organization that manifests as mechanical directionality and nonlinearity. For supporting ligaments in the knee, constitutive theories have been developed to address these issues—predominately assuming transverse isotropy with the preferred material direction aligned with structural collagen. However, with the abundance of constitutive theories available it can often be difficult to differentiate among them, and this selection can be complicated by new and conflicting mechanical characterization data. This work rigorously describes the process by which candidate constitutive theories can be evaluated in the context of transverse hyperelasticity using quasi-static stress–strain experimental data of the medial collateral ligament (MCL) of the knee. We show how recent data of the MCL fails to be accurately represented using previously validated and generally accepted constitutive theories. We expand the pool of candidate theories to include chain-based statistical mechanics and hybrid theories to explore the range of representative models of the MCL. This novel hybrid theory, constructed by superposing a slightly compressible, isotropic eight-chain MacKintosh network model with a phenomenological directional component, is shown to have superior performance in the representing the quasi-static stress–strain behavior of the MCL, particularly in the transverse direction. Using a simplified finite element model of ligament deformation, implicit structure among theories is examined using a straightforward framework for developing computational material models.

1. Introduction

Ligaments are soft tissue structures that span the gaps between bones, connecting them together. Macroscopic joint motion and stability are coordinated and maintained by ligaments in combination with additional soft tissue structures like muscles, articular cartilage, menisci, and tendons. Ligaments support and direct normal joint motions, while acting to resist potentially harmful motions. While ligaments often play a critical role in mitigating the risk of a traumatic event—either contact or noncontact—from resulting in acute injury, ligaments do fail. This failure may be catastrophic, as in ligament rupture resulting in hyper-mobility of the joint. Alternatively, in progressive ligament injuries microscopic damage accumulates, leading to structural and mechanical changes within the tissue bulk. These subtle changes in ligament mechanical behavior and structural geometry can have a significant impact on total joint motion, as well as local deformation in the joint; deviations from expected local tissue deformations can potentially lead to collateral tissue degenerative diseases, like osteoarthritis (OA).

Ligament failure is both prolific and complex. The anterior cruciate ligament (ACL) is the most commonly injured supporting ligament in the knee, with over 175,000 surgical reconstructions performed annually in the United States (Spindler and Wright, 2008), and, problematically, the average age of those affected by soft tissue injury is dropping drastically (Ingram et al., 2008; Kim et al., 2011b). Yet, even with the nearly 90% short term success rate of ACL reconstruction (Wright et al., 2008), these injuries are linked to increased susceptibility for collateral soft tissue diseases, like OA (Kessler et al., 2008)—a disease that already affects over 15% of the adult United States population (Lawrence et al., 2008). The existence and frequency of ligament injury, and its contribution to secondary soft tissue injuries and diseases, has motivated researchers and clinicians to examine their mechanical behavior in myriad contexts. Experimental studies have explored macroscopic

---

[*] Corresponding author.
E-mail address: bmarchi@umich.edu (B.C. Marchi).

https://doi.org/10.1016/j.ijsolstr.2018.01.017

Please cite this article as: B.C. Marchi et al., Evaluating continuum level descriptions of the medial collateral ligament, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.01.017

joint motion in healthy and ligament-deficient knees (Berchuck et al., 1990; Noyes et al., 1992; Georgoulis et al., 2003; Morrison, 1970), ligament injury mechanisms (Boden et al., 2000; Olsen et al., 2004; Hewett et al., 2005; Krosshaug et al., 2007), reconstructive techniques (Hughston and Eilers, 1973; Yagi et al., 2002; Kurosaka et al., 1987), and rehabilitation protocols (Shelbourne and Nitz, 1990; Beynnon et al., 1995).

Given the fundamental role of ligaments in maintaining joint functionality, a mechanistic understanding of ligaments is critically important. The mechanics of individual ligament structures can provide insights into the specific contributions of a particular ligament in preserving joint integrity, minimizing the risk of injury, and potential mechanical pathways of ligament injury. A mechanical appreciation of ligaments can also be instrumental in investigating, evaluating, and differentiating between clinical interventions. Experimental efforts at this low level have indeed furthered our characterization and understanding of ligaments; however, experimental studies, particularly related to experimental biomechanics, have a number of irreconcilable limitations, including structural and geometric specimen-to-specimen variability, low spatial and temporal resolution, prohibitive specimen acquisition and storage costs, and an inability to describe deformation states generally.

Where experiments are limited, computational tools and models have the potential to excel. Computational models, particularly finite element (FE) models, can provide specific information on individual tissue contributions with respect to global joint function, as well as the coupling and coordination among tissues during macroscopic joint motions. Computational models offer precise, full-field, and complete descriptions of deformation manifesting from normal motions (Marchi and Arruda, 2017; Peña et al., 2006a; Mootanah et al., 2014; Limbert et al., 2004; Zhang et al., 2008; Xie et al., 2009; Song et al., 2004; Gardiner and Weiss, 2003; Shelburne et al., 2006; Donahue et al., 2002; Beillas et al., 2004; Adouni et al., 2012), injury causing activities (Kiapour et al., 2014a; Abdel-Rahman and Hefzy, 1998; Penrose et al., 2002; Quatman et al., 2011), injured and diseased joints (Peña et al., 2007; Shirazi and Shirazi-Adl, 2009b; Weiss et al., 1998; Manda et al., 2011; Mootanah et al., 2014; Marchi et al., 2017; McLean et al., 2011), and reconstructive procedures (Bae et al., 2016; Huang et al., 2012; Kim et al., 2011a; Godest et al., 2002; Halloran et al., 2005; Ramaniraka et al., 2007; Westermann et al., 2013; 2017; Peña et al., 2005b; 2006b). FE models also afford a convenient platform for the systematic evaluation of relevant geometric and mechanical properties through parametric studies (Kiapour et al., 2014b; Donahue et al., 2003; Peña et al., 2005a; Shirazi and Shirazi-Adl, 2009b; 2009a; Wang et al., 2014; Atmaca et al., 2013; Marouane et al., 2014; Li et al., 2002; Shin et al., 2007; Wan et al., 2013; Baldwin et al., 2012; Mesfar and Shirazi-Adl, 2005) and have the potential to conduct clinically meaningful, individualized joint analyses (Gardiner and Weiss, 2003; Jones et al., 2015).

The accessibility and power of FE models have pushed forward our understanding of tissue-level contributions to joint mechanics, but with so much available information researchers must be judicious in evaluating the significance of studies. Constitutive models of individual tissues dictate the basic physics of any structural biomechanics analysis; however, they are often relegated to minutia of methods sections and rarely examined in a systematic or forthright manner. Constitutive models need to be evaluated on their ability to describe observed deformation, while simultaneously predicting deformations not used in their construction. Often whole joint computational models rely on a single set of experimental data—which may or may not sufficiently describe all the relevant physics—and the weight of precedent to build soft tissue material behaviors. This approach is convenient, but not very elastic to new or conflicting experimental observations.

With an eye towards adaptability and implementation, this work seeks to test the hypothesis that the commonly employed family of invariant-based transversely isotropic, exponential models is capable of capturing the bulk mechanical response of knee supporting ligaments. Specifically, the appropriateness of various transversely isotropic, hyperelastic constitutive models containing a single material direction are examined, using the commonly adopted Holzapfel–Gasser–Ogden (HGO) model as a benchmark. Constitutive forms are assessed in the context of their ability to describe historic and current quasi-static experimental stress–strain behaviors of the medial collateral ligament (MCL). The HGO model is evaluated on its ability to capture both longitudinal and transverse deformations and compared to alternative transversely isotropic, hyperelastic material models. This work shows that the traditional HGO model is largely able to capture the response of the MCL based on historic data. However, the model, as it is traditionally posed, is less flexible to data that are more anisotropic and nonlinear, like those found in recent efforts. Therefore, the HGO model, and those of its type, may be ill-suited to describe the complete physics of the ligament. Representative constitutive theories are critically important when building descriptive models that incorporate real deformations, which potentially include multi-axis loading and shear. This failure motivates the need to systematically assess the appropriateness of a larger pool of candidate constitutive theories, including novel theories, for describing ligaments. In addition to gauging their descriptive performance, candidate theories were incorporated into a simple, three-dimensional FE model to evaluate how constitutive form affects bulk deformation.

2. MCL experimental characterization

The addition of directionality in constitutive models requires knowledge of the material response in multiple loading configurations. This need has led to the application of traditional mechanical characterization techniques to capture the stress–strain behavior of tissues assumed to be transversely isotropic, like ligaments (Quapp and Weiss, 1998; Henninger et al., 2013; 2015; Lujan et al., 2007; Butler et al., 1990). In particular, tension experiments have been used to determine the bulk response of ligaments along (longitudinal) and normal (transverse) to the preferred material direction. In the case of ligaments, the material orientation is typically assumed to be aligned with the mean orientation of collagen fibers (Debski et al., 2003; Weiss et al., 2005).

In this work, both historic (Quapp and Weiss, 1998) and recent (Henninger et al., 2013; 2015; Lujan et al., 2007) experimental efforts were used as the foundation of the assessment of each candidate constitutive theory. Fig. 1 illustrates the unidirectional mechanical response of cadaveric human MCLs along (Fig. 1(a)) and normal to (Fig. 1(b,c)) the highly aligned collagen fibers of the ligament. Typically, the preferred stress–strain response of soft tissues is characterized by two physiologically relevant domains: the toe and linear regions. The toe region is associated with initial nonlinearity observed at relatively small stretches, while the linear region is said to occur beyond some transition stretch after which the stress–strain response is nearly linear. For example, a visual inspection of the longitudinal stress–strain behavior presented in Quapp and Weiss (1998) (Fig. 1(a)) might lead one to conclude a transition between the toe and linear regions at approximately $\lambda_{11} = 1.02$ in the longitudinal direction.

While not considered herein, the real interactions between ligament macromolecules and between solid and liquid constituents tend to result in time and history dependent deformation physics. Creep and stress relaxation experiments have been used to help explore the response of ligaments in the time domain (Woo et al., 1981; Grood and Noyes, 1976). Looking at multiple strain levels during stress relaxation experiments, it has been shown that there

Please cite this article as: B.C. Marchi et al., Evaluating continuum level descriptions of the medial collateral ligament, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.01.017